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Original Paper

Analytical investigation of structural elements produced from sustainable waste tire-based geopolymer for infill wall applications

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ABSTRACT

With the increasing global population, various industrial demands have emerged. In response to these needs, construction and shelter have become fundamental aspects of human life, leading to rapid growth in the construction sector. However, the accelerated depletion of natural resources commonly used in industry poses a significant challenge to sustainability. The use of conventional building materials results in excessive consumption of natural resources and generates waste that can lead to irreversible environmental problems. This situation necessitates the investigation of new and sustainable alternatives to minimize the environmental impact of human activities. As a natural consequence of expanding industries driven by technological advancement, the volume of industrial waste is growing rapidly. The wastes must be either stored, disposed of, or reused. Considering the environmental damage associated with storage and disposal, the most appropriate solution is reuse, which contributes to sustainability by transforming waste into secondary raw materials. In this study, a combination of waste tires, marble waste, and bottom ash was utilized alongside pumice, a natural and lightweight aggregate. To facilitate the geopolymerization process, sodium hydroxide was employed in the preparation of the alkaline activating solution. The resulting geopolymer-based construction material was then evaluated for its potential application in reinforced concrete structural system. Stress-strain relationship of the sustainable geopolymer mixture, primarily derived from waste tires, were experimentally determined. Furthermore, the analytical performance of masonry units manufactured from this mixture was evaluated in infill wall-frame systems.

I. INTRODUCTION

Concrete is currently the most widely used construction material in the building industry. With the increasing pace of urban development, concrete consumption has risen rapidly. The component of concrete that contributes most significantly to both cost and environmental concerns is cement. In a study investigating the use of sustainable and environmentally friendly materials for the construction of modern buildings in the construction sector, it was noted that due to the substantial greenhouse gas emissions released into the atmosphere during the production of Portland cement, alternative materials are being sought. The use of geopolymers was highlighted as both environmentally beneficial and energy-efficient [1]. Materials found in industrial waste can be utilized as secondary raw materials due to their pozzolanic properties, thereby serving as potential alternatives to cement. In industrial facilities, waste formed at the bottom of furnaces as a result of fossil fuel combustion is referred to as bottom ash. Another type of such waste is boiler slag. Since the properties of these by-products vary depending on the type of coal burned, storage conditions, combustion duration, and temperature, they are not considered standardized secondary products. However, when ground, their pozzolanic characteristics are enhanced [2]. Due to their limited application areas, these wastes pose significant environmental challenges [3, 4]. In the literature, a study involving the alkali

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activation of bottom ash sourced from a thermal power plant resulted in the production of geopolymer mortar. The author evaluated parameters such as unit weight, ultrasonic pulse velocity, flexural and compressive strength, setting times, and volume stability of the mortar [5]. Another study reported that approximately 15 million tons of fly ash and 4 million tons of bottom ash are generated annually from thermal power plants, and the production of one ton of cement releases roughly one ton of CO_2 into the atmosphere [6]. In a separate investigation into the use of ground granulated blast furnace slag and bottom ash in concrete mixtures, it was noted that granulated slag, a major by-product of the iron and steel industry, possesses both pozzolanic and binding properties. The study described bottom ash as a micro-scale waste material that accumulates beneath the combustion chamber in coal-fired thermal power plants. Due to its amorphous, siliceous and aluminous composition, bottom ash exhibits pozzolanic behavior and can be used as an additive in concrete. Within the scope of the article, a sustainable geopolymer mixture containing bottom ash was analytically examined for its applicability in infill wall systems [7]. In contemporary conventional construction systems, infill wall applications occupy a significant volumetric share. The utilization of industrial waste materials in these applications has the potential to yield substantial economic benefits. Moreover, such practices contribute meaningfully to the Zero-Waste Vision of Türkiye by promoting sustainable resource management.

On the other hand, with the increase in population and advancing technology, vehicle usage has significantly risen. For safe operation, tires have a limited-service life, and once this lifespan is exceeded, they pose a substantial environmental waste problem. The storage of these end-of-life tires requires large volumes of space, and over time, they have the potential to release harmful chemicals into the soil, thereby causing environmental damage [8]. In the construction sector, the incorporation of waste tires is believed to enhance the ductility and lightness of concrete [9]. A study was conducted on the effects of waste tires in cement-based composite mixtures and reported improvements in compressive, flexural, and tensile strengths at 7 and 28 days while tire content was increased [10]. Another investigation focused on the use of end-of-life tires, which constitute a major waste issue, in concrete mixtures. It was found that the addition of waste tires contributed to the production of lightweight concrete and improved flexural toughness, thereby facilitating waste disposal. Experimental results indicated a reduction in unit weight in fresh concrete, difficulty in passing through reinforcement with increasing fiber length, and a decrease in dry unit weight in hardened concrete [11]. A study focused on the use of waste materials in concrete included mostly recyclable materials. The research explored the recycling of waste tires and their incorporation into concrete. Experimental efforts aimed to produce high-strength, low-density concrete types with enhanced thermal and acoustic insulation for energy-efficient buildings. Tests conducted on samples in which waste materials were substituted with aggregates at varying proportions, it was revealed that there was a decrease in both strength and density. Conversely, significant improvements were observed in thermal and sound insulation properties [12]. In another study, an investigation on the impact of waste tires on concrete mixtures was conducted. It was noted that millions of vehicle tires worldwide reach the end of their useful life and become waste. To mitigate their environmental impact, it was suggested that these materials should be repurposed as by-products in sustainable applications. The study observed that increasing the amount of waste tire in all mixtures led to reductions in unit weight and compressive strength [13]. A further investigation examined the sustainable use of industrial wastes such as waste tires, fly ash, and ground granulated blast furnace slag in the production of geopolymer concrete. In this study, geopolymer mixtures were produced by substituting waste tires for aggregates in various proportions, alongside fly ash and slag, and subjected to different curing temperatures. The tests revealed that rubber fibers

caused a partial reduction in mechanical strength, and high temperature curing negatively affected the performance of geopolymer concrete. Literature reviews indicate that the mechanical properties of concrete mixtures designed with waste tire additives may be adversely affected. Therefore, analytical studies have focused on evaluating the applicability of sustainable geopolymer mixtures containing waste tires in infill wall construction [7]. Thermal and acoustic advantages of waste tire-based mixtures have been identified in the literature. Accordingly, it was considered that infill wall units produced from sustainable geopolymer mixtures incorporating such waste materials may offer additional benefits beyond merely enhancing the ductility capacity of structural frames.

Another type of waste generated within the construction sector arises from marble production. Marbles, which are frequently used in interior and exterior cladding, flooring, kitchen countertops, bathrooms, stair treads, and decorative elements, produce waste during both extraction from quarries and the cutting of blocks and slabs to meet design specifications. The resulting marble waste can be utilized as aggregate and repurposed as a construction material [14]. In one study involving marble dust, acidic pumice sourced from the Nevşehir region was used as aggregate, while industrial waste marble dust obtained from the Kırşehir region was incorporated into self-compacting lightweight concrete as a partial replacement for cement at varying ratios. The study emphasized the significance of marble dust usage in terms of both environmental pollution mitigation and sustainability [14] . In another investigation, the use of waste marble generated from quarry operations and end-of-life waste tires was evaluated as a means to reduce their adverse environmental impacts by incorporating them into concrete mixtures.

The authors noted that such utilization could both prevent environmental harm and yield more cost-effective materials. In this study, marble dust and waste tires were substituted at low ratios for fine and coarse aggregates. Experimental results indicated that while the inclusion of waste tires led to a reduction in mechanical strength, the production of environmentally friendly concrete using marble dust alone was feasible, and the combined use of both waste materials was deemed suitable for concrete production [15]. The article further includes a sustainable geopolymer mixture [7] selected for analytical studies, which incorporates waste marble. The reduction in strength caused by the addition of waste tires can be compensated for by the presence of waste marble. The use of unit elements produced from geopolymer mixtures based on waste and natural materials in the construction of infill walls is considered significant for promotion of recyclable green building concepts.

To minimize the weight of structural units produced from geopolymer mixtures based on waste materials analytically examined for use in infill wall construction pumice was selected as a key component [7]. Pumice is a naturally occurring volcanic rock characterized by independent pores formed through volcanic activity. It has been utilized in the construction industry for many decades. In the preparation of geopolymer paste, pumice serves as a natural pozzolanic material, while bottom ash is considered as an artificial pozzolan. Although pumice and bottom ash are selected for their pozzolanic properties, pumice is significantly lighter than bottom ash, thereby contributing to weight optimization within the mixture. A study investigated geopolymer concrete incorporating pozzolanic waste materials, considering the environmental impact and high energy demand associated with cement production. Given the limited availability of conventional pozzolans, the need for alternative sources was emphasized. The study aimed to improve cost-efficiency, microstructure, and mechanical properties using alternative pozzolans. It was found that ground coarse pumice and expanded perlite exhibited pozzolanic activity, suggesting their potential as cement substitutes. The authors concluded that the materials mentioned above could contribute to reductions in both cost and carbon emissions [16]. In another study, fly ash-based geopolymer was

proposed as an alternative to Portland cement. The increasing use of vehicles has led to environmental concerns regarding waste tires, prompting their evaluation as aggregate replacements in lightweight concrete. The combined use of pumice and waste tires instead of sand resulted in reductions in both compressive and flexural strength. As the proportion of waste tires and pumice increased, water absorption also rose, while unit weight and workability decreased. Thermal conductivity values were observed to decline with higher tire content compared to reference samples. The author highlighted the positive contribution of waste tires to insulation performance, marking a significant step toward the development of sustainable construction materials. Due to their pozzolanic nature, these materials cannot achieve sufficient strength independently and must undergo chemical activation. The geopolymerization process was initiated by using sodium hydroxide, a widely available and commonly used alkali activator with broad applicability. Within this framework, a construction material composed entirely of waste and natural components was developed, exhibiting high thermal resistance and acceptable strength parameters for use in masonry units [7]. The study analytically evaluated the applicability of the mentioned material in the construction of infill walls.

Infill walls are non-load-bearing structural components constructed using masonry units to fill the voids within reinforced concrete frames. Their exclusion from the load-bearing system is attributed to several factors, including material behavior, discontinuity between structural and non-structural elements, insufficient design standards, complex seismic responses, and the need for advanced design and analysis methodologies. In structural analyses, infill walls are typically modeled only as vertical loads on the frame and are not considered in terms of structural capacity [17]. Consequently, infill walls contribute to the dead load of the structural system. Reducing the weight of the masonry units used in infill wall construction directly decreases the overall structural weight, which in turn has a favorable impact on seismic load performance. The primary function of infill walls, whether used internally or externally, is to partition interior spaces. These walls also provide insulation against parameters that may adversely affect the building and its occupants, such as fire, moisture, sound, and heat. Hollow clay bricks, despite their low compressive strength and limited contribution to lateral seismic resistance due to their high void ratio, enhance energy efficiency by reducing heat transfer through the wall [18]. Autoclaved aerated concrete and concrete blocks with porous structure, are lightweight and thus beneficial in reducing overall structural weight. Their porous nature also imparts superior thermal and acoustic insulation properties. Additionally, these materials are non-combustible and resistant to high temperatures, offering a significant advantage in terms of fire safety. Despite these benefits, infill walls are prone to brittle failure under seismic loading, which can result in substantial damage [19].

Therefore, it is essential that the masonry units used in infill wall construction possess not only thermal and acoustic insulation capabilities but also be lightweight, durable, and exhibit high deformation capacity. The sustainable geopolymer mixture proposed in the referenced study was specifically designed to meet these criteria, utilizing waste and natural materials. The behavior of masonry units produced from this mixture was analytically examined in the context of infill wall performance. The study evaluated the applicability of this material in infill wall construction, which represents a broad area of implementation within the construction sector. The article aims to contribute to both academic and industry-oriented research in areas such as waste recycling, sustainability, reduction of carbon emissions, valorization of waste materials, and the development of advanced construction materials and innovative structural products. Accordingly, reinforced concrete frame with infill wall system was

modelled and the material properties were obtained from experiments. Pushover analyses were applied to the frame system and the response of the system was then evaluated.

II. METHOD

In this study, the geopolymer mixture developed by Sezen through extensive experimental trials was adopted as the basis [7]. The potential use of structural units produced from this mixture as infill wall materials within reinforced concrete frames was analytically investigated. The analyses were conducted using SAP2000 software, and static pushover analysis was applied to the frames [20].

2.1 Reference Geopolymer Mixture for Analytical Study

The detailed components of the geopolymer mixture adopted in this study are presented in Table 1[7]. As shown in Table 1, the mixture comprises bottom ash, coarse pumice, waste marble, and recycled rubber in specific proportions. The material weights presented in Table 1 correspond to the quantities used in a production batch with a total volume of 1018 cm^3, comprising three specimens measuring 4×4×16 cm and two specimens measuring 5×5×5 cm. The mixture exhibits geopolymeric characteristics and is composed entirely of natural and waste-derived materials [21]. In the sustainable geopolymer mixture based on waste tires, sodium hydroxide (NaOH) was selected as the alkali activator. Solutions with varying molarities were prepared and based on a comprehensive literature review and preliminary experiments, 12 M was identified as the optimal concentration. For each molarity level, 40 grams of NaOH were added per liter of distilled water during solution preparation. Different 21 mixing ratios were tried to obtain the reference geopolymer mixture. With the mixture given in Table 1, the most ideal result has been achieved in terms of setting, workability, unit volume, weight and mechanical properties [7] [20]. In this article, the use of the most ideal mixture obtained in infill wall frames is examined analytically.

Table 1. Composition of bottom ash and pumice-based geopolymer mixture [7]

	Bottom Ash (g)	**Pumice (g)**	**Waste Marble (g)**	**Waste Tire (g)**	**Alkaline Activator (g)**
Geopolymer	350	75	25	50	280 (12 M)

In the study conducted by Sezen [7], laboratory tests were performed on specimens produced from the geopolymer mixture, including a flexural strength test (Fig. 1) and a compressive strength test (Fig. 2). After heat curing and successful completion of the setting process, the specimens were subjected to mechanical performance tests. According to the TS EN 196-1 standard, the flexural strength test was conducted first, followed by the compressive strength test. The flexural strength test was performed using the three-point bending method on beam specimens measuring 4×4×16 cm. Subsequently, the same specimens were tested for compressive strength. Additionally, cube specimens with dimensions of 5×5×5 cm and 15×15×15 cm was used for compressive strength testing. Finally, to determine the stress–strain curve, a test was conducted on a cylindrical specimen measuring 15×30 cm. This test enabled the evaluation of mechanical properties such as elastic modulus and deformation capacity. In total, three flexural tests and ten compressive tests were performed. The average compressive strength was calculated as 4.3 MPa, with a standard deviation of 0.79 MPa. For flexural strength, the average value was 0.93 MPa, and the standard deviation was 0.15 MPa. In addition to these findings, a thermal conductivity test was

performed on a specimen measuring 5×15×15 cm, and the thermal conductivity coefficient was calculated as 0.47 W/mK. These results indicate that the material exhibits values that are acceptable within industry standards. The comparative table of the selected geopolymer mixture and its industry counterparts indicated that the material exhibits properties consistent with insulation materials (Table 2). Nevertheless, further physical and durability tests are required. It was observed that the proportion of each component within the geopolymer significantly affects its physical, mechanical, and durability characteristics. Therefore, achieving a single standardized geopolymer mixture is highly challenging. The critical factor is the ability to define the expected mechanical and durability behavior of the unit element produced from the geopolymer mixture. In this context, mixture optimization tailored to specific needs and the production of structural elements from the optimized mixture can be realized. Based on the experimental findings, the stress–strain curve obtained is graphically presented in Fig. 3. This graph illustrates the specimen's behavior under loading and provides insights into its energy absorption capacity and deformation characteristics. The unit weight of the geopolymer specimens was determined to be 0.72 ton/m³ [7].

Table 2. Comparison of geopolymer material with industry counterparts [22-24]

Building Material/Parameter	Bims	Autoclaved Aerated Concrete (AAC)	Clay brick	Geopolymer mixture
Compressive Strength	2,5 MPa	4 MPa	2.5 MPa	4.3 MPa
Flexural Strength	1 MPa	1.1 MPa	-	0.93 MPa
Thermal transmittance coefficient	0.18 W/mK	0.11 W/mK	0.32 W/mK	0.47 W/mK
Unit Volume Weight	0.65 ton/m^3	0.4 ton/m^3	0.7 ton/m^3	0.72 ton/m^3



Figure 1. Geopolymer mixture flexural strength test

In SAP2000 software, the potential enhancement of lateral load capacity resulting from the use of the developed geopolymer mixture as an infill wall material in reinforced concrete structures was investigated through comparative frame pushover analysis models. In the analytical study, the experimental stress–strain curve obtained from the specimen was adopted as the basis for the material model.



Figure 2. Compressive strength test of the geopolymer mixture

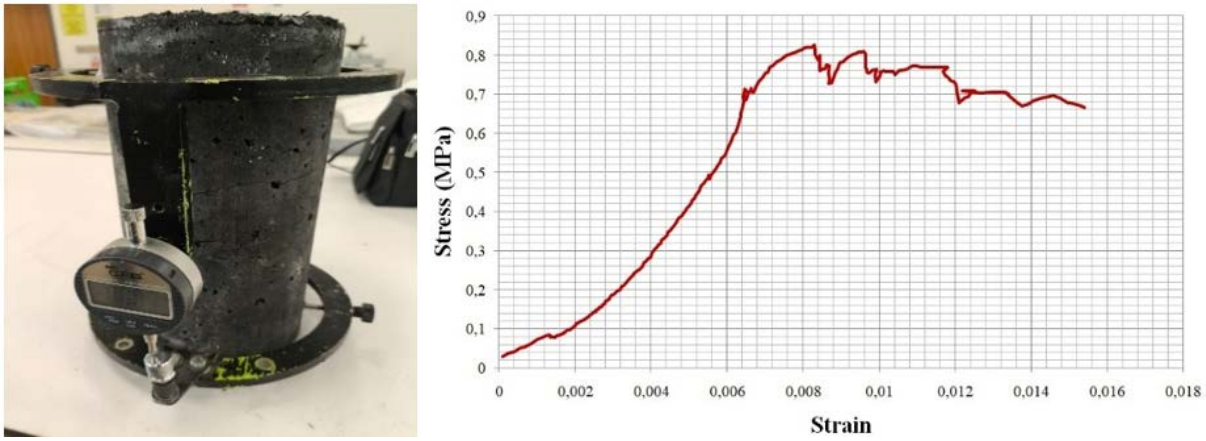

Figure 3. Stress – strain graph of the cylinder of the geopolymer mixture

2.2 Analytical Studies

Within the scope of this study, the potential applications of the geopolymer material composed entirely of waste and natural components in various construction contexts were analytically evaluated. As an initial investigation, the use of 100×100×200 mm unit elements from the material as infill walls was examined analytically in terms of their contribution to the load-bearing capacity of reinforced concrete frames. For this purpose, a reference frame (without any infill wall) was modeled using SAP2000 software. The reference frame has a height of 3000 mm and a span of 6000 mm. The column dimensions are 400×400 mm, while the beam dimensions are 250×500 mm (Fig. 4). The concrete material used in the frame was defined as C30.

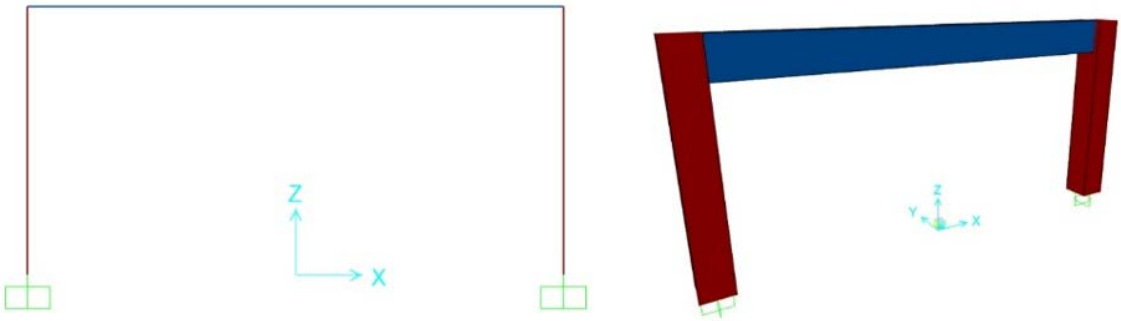

Figure 4. Reference frame model [20]

A static pushover analysis was applied to the reference frame model. Axial loads were introduced to the columns at a ratio of $N/N_0 = 0.1$. For both columns and beams, a fiber hinge modeling approach was adopted (Fig. 5).

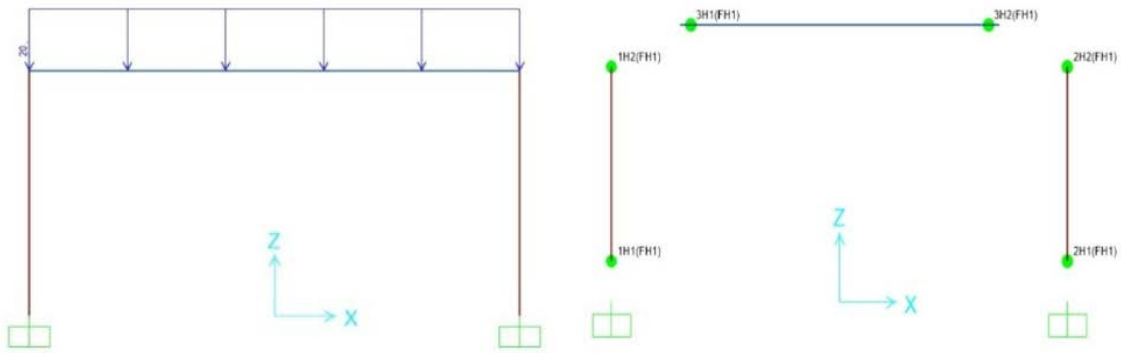

Figure 5. Reference frame plastic hinge description [20]

A deformation-controlled pushover analysis was conducted, resulting in the generation of a static pushover curve. According to this curve, the reference frame exhibited a maximum base shear capacity of 183.68 kN and a peak lateral displacement of 72.95 mm (Fig. 6).

In the reference frame, geopolymer unit elements with the dimension of 100×100×200 mm was modelled as infill walls. The modeling was carried out using equivalent compression struts, based on the equations provided in Sections 15C.1 and 15C.2 of the Türkiye Building Earthquake Code (TBEC-2018), specifically mentioned in the Section of 15C.2 *"Strengthening of Infill Walls with Welded Wire Mesh and Special Plaster"* (Eq. 1, Eq. 2) [25-27].

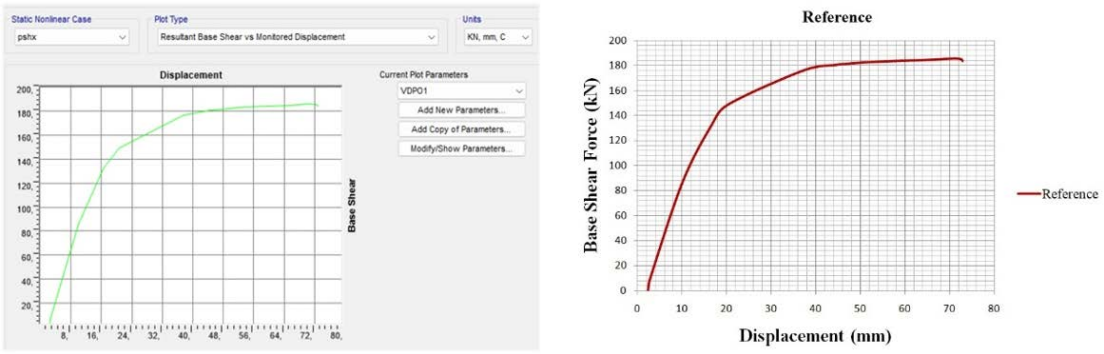

Figure 6. Reference frame Pushover analysis result

TBEC-2018 equivalent compression struts modeling formulas:

$$a_d = 0.175\,(\lambda_d\, h_k)^{-0.4}\, r_d \tag{1}$$

$$\lambda_d = \left[\frac{E_d\, t_d \sin 2\theta}{4 E_c\, I_k\, h_d}\right]^{\frac{1}{4}} \tag{2}$$

Based on the stress–strain graph presented in Fig. 3, the elastic modulus (E) of the geopolymer material was calculated as 100 MPa. In the relevant equations, E_d denotes the elastic modulus of the infill wall, t_d the thickness of the infill wall, θ the angle between the equivalent compression strut and the horizontal axis, E_c the elastic modulus of the frame concrete, I_k the moment of inertia of the column, h_d the height of the infill wall, λ_d the equivalent strut coefficient, h_k the column height, r_d the diagonal length of the infill wall, and a_d the width of the equivalent compression strut. After calculating all these parameters, the equivalent strut width for the geopolymer mixture was determined to be 1.04 m, as shown in Table 3. The equivalent compression strut defined by the elastic modulus and thickness of the infill wall was modeled in SAP2000 within the reference frame. A static pushover analysis was then performed on the frame incorporating the geopolymer material, and a fiber hinge model was also applied to the axial compression strut (Fig 7).

As a result of the analysis, the capacity curves of the reference frame and the frame incorporating waste tire-based infill walls were compared (Fig. 8). When the two static pushover curves were examined, an increase of 4.9% in maximum base shear and 2.77% in lateral displacement was observed.

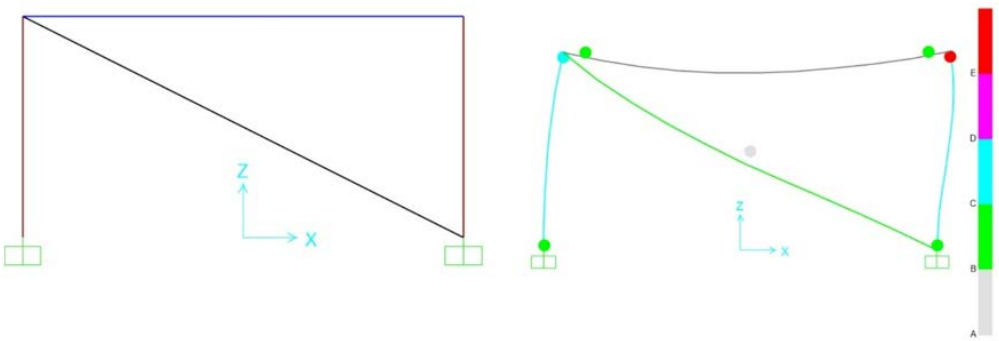

Figure 7. Geopolymer mix unit element wall model static pushover analysis [20]

Table 3. Calculation of equivalent pressure strut width for geopolymer material

E_d (MPa)	t_d (m)	$sin2\theta$	E_c (MPa)	I_k (m^4)	h_d (m)	r_d (m)	λ_d	h_k (m)	a_d (m)
100	0.1	0.86	31000	0.002	2.4	6.09	0.35	3.0	1.04

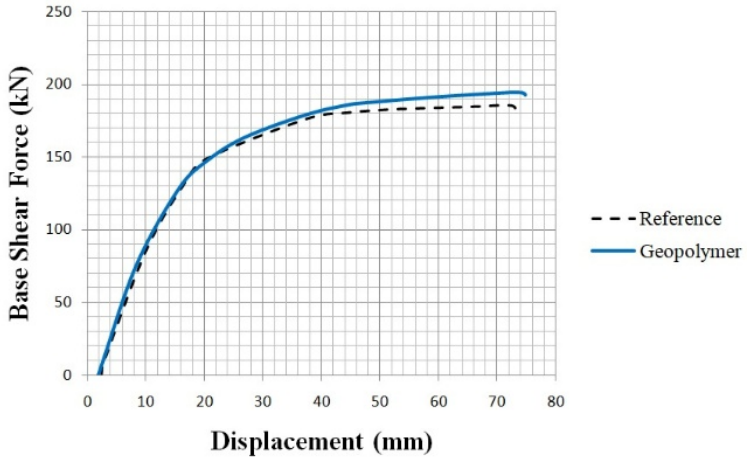

Figure 8. Comparison of frame capacity with reference and geopolymer material infill wall

Experimental studies have shown that as the dimensions of unit elements made from waste tire increase, incomplete internal curing adversely affects strength parameters. Consequently, it is assumed that reducing the size of the unit elements may lead to an increase in their elastic modules. Based on this approach, a second analysis was conducted by considering a variation in which the elastic modulus of the infill wall could reach 500 MPa. Because it has been determined by Sezen that as the sample sizes decrease in experimental studies, increases of up to 5 times in the strength parameter are observed [7]. The equivalent compression strut width corresponding to an elastic modulus of 500 MPa was calculated, and the results are presented in Table 3. A static pushover analysis was performed using the values provided in Table 4 and compared with the previous two analyses (Fig. 9). As a result of assuming an elastic modulus of 500 MPa, the maximum base shear capacity increased by 6% compared to the reference frame. However, as observed in Fig. 10, this increase in elastic modulus did not lead to a significant improvement in overall structural capacity.

Table 4. Calculation of equivalent pressure strut thickness for E = 500 MPa

E_d (MPa)	t_d (m)	$sin2\theta$	E_c (MPa)	I_k (m^4)	h_d (m)	r_d (m)	λ_d	h_k (m)	a_d (m)
500	0.1	0.86	31000	0.002	2.4	6.09	0.51	3.0	0.89

Within the scope of this study, the potential effect of coating the geopolymer material with a high-strength material was examined. A unit element with a cross-sectional area of 100×100 mm² and an elastic modulus of 500 MPa was theoretically coated in all directions with a material possessing an elastic modulus of 28000 MPa and a thickness of 20 mm. Based on area-weighted averaging, the resulting composite elastic modulus was calculated as follows: (100/196)x500+(96/196)x28000=255+13714=13969MPa [28]. This calculation was derived from a theoretical approach found in the literature. This model depended on the volume fraction of components of the composite. In practice, when a structural element composed of waste tire is coated with a different material, the interaction between the two materials must be experimentally observed to assess their composite behavior. In the

analytical study presented here, the effect of forming a new composite material by coating the waste tire-based structural unit with a mechanically superior material on the overall frame behavior was investigated. Based on the theoretical elastic modulus of 13969 MPa obtained from the literature, the equivalent compression strut width was calculated and presented in Table 5.

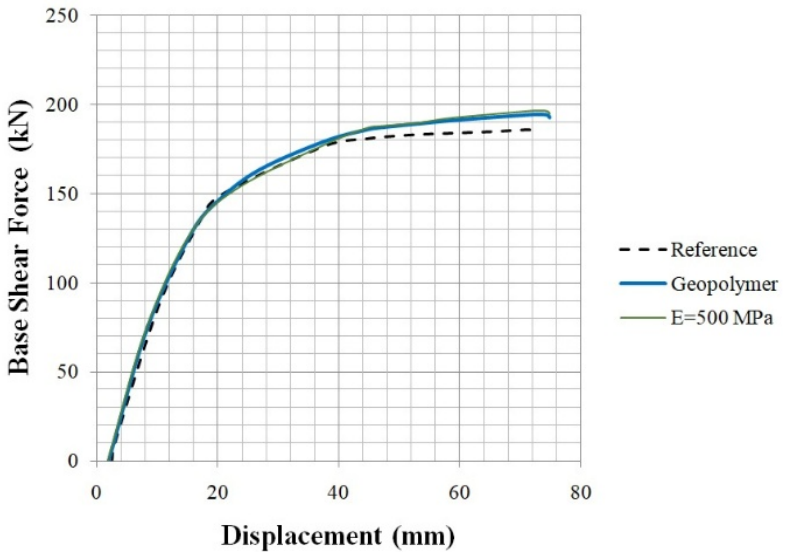

Figure 9. E = 500 MPa, comparison of geopolymer material and reference frame capacity

Table 5. Calculation of equivalent pressure strut thickness for E = 13969 MPa

E_d (MPa)	t_d (m)	$sin2\theta$	E_c (MPa)	I_k (m^4)	h_d (m)	r_d (m)	λ_d	h_k (m)	a_d (m)
13969	0.1	0,.6	31000	0.002	2.4	6.09	0.35	3.0	0.64

When all static pushover analysis results are compared, the variation involving the coating of the geopolymer material with a high-strength layer resulted in a 19.6% increase in maximum base shear capacity (Fig. 10). However, this value may vary depending on the mechanical properties of the coating material and the bond quality between the coating and the waste tire-based substrate. Additionally, the characteristics of the mortar used for assembling the unit elements may also influence this parameter.

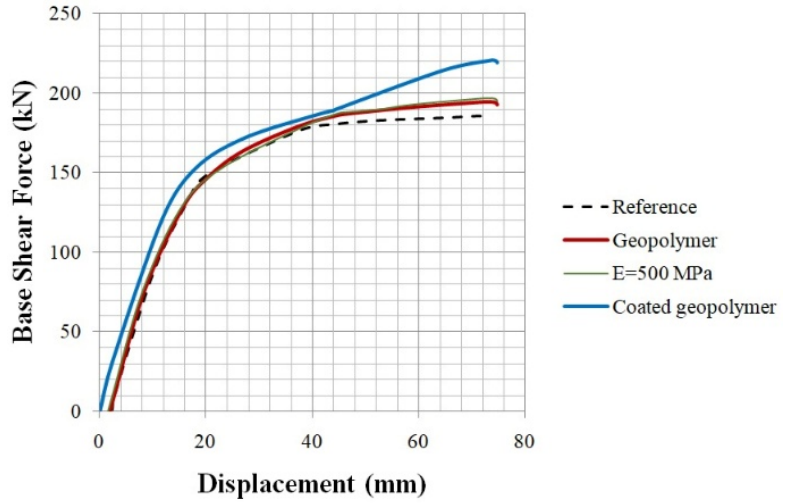

Figure 10. Comparison of capacity curves of all analyses

III. RESULTS AND DISCUSSIONS

Comprehensive analytical investigations were conducted within the scope of the study to evaluate waste tire-based geopolymer mixtures as structural materials. Accordingly, the mechanical strength, physical properties, and overall performance of the developed geopolymer mixture were examined in detail, and its suitability for engineering applications was assessed from multiple perspectives. In particular, the potential use of waste tire-reinforced geopolymer material as an infill wall element in structural systems was evaluated through analytical methods, focusing on its effects and potential advantages in non-load-bearing infill wall systems.

The key findings from the analytical evaluations are as follows:

- Analysis of the stress–strain curve obtained from cylindrical specimens produced using the geopolymer mixture revealed that the material exhibits considerable ductility.
- The elastic modulus derived from the stress–strain curve was used as a reference parameter during the analytical modeling process for defining the geopolymer material in SAP2000 software.
- A bare frame was modeled and subjected to nonlinear static pushover analysis. The resulting capacity curve was obtained. Subsequently, an infill wall composed of the geopolymer mixture was modeled within the frame using the equivalent strut method in accordance with the Türkiye Building Earthquake Code (TBEC-2018), and pushover analysis was repeated. The results indicated a 4.9% increase in base shear force.
- The elastic modulus of the geopolymer material was determined to be approximately 100 MPa based on cylindrical specimen tests. However, due to factors such as specimen size, internal curing conditions, and structural imperfections, this value is expected to result in lower compressive strength in large-scale specimens. It was observed that smaller specimens would yield higher elastic modulus values in stress–strain tests. When the elastic modulus was assumed to be 500 MPa, the maximum base shear force increased by 6% compared to the reference frame.
- The analysis revealed that the mixture composed entirely of waste and natural materials requires surface reinforcement with a high-strength material to be effectively used as an infill wall in conventional structures. Specifically, theoretical modeling suggested that coating the geopolymer with a 20 mm layer of cement-based composite could increase the elastic modulus and result in a base shear force enhancement of up to 19.6%.
- The waste tire-based geopolymer with high deformation capacity, was found to positively influence the lateral load-bearing performance of infilled frame systems.
- The findings demonstrated that these materials possess high deformation capacity and can enhance the energy dissipation capacity of infilled frame systems. Due to their low unit weight, they may be preferred in infill wall applications. However, considering strength and health criteria, composite solutions involving coatings with other construction materials may be necessary.

IV. CONCLUSIONS AND LIMITATIONS

Within the scope of this study, the sectoral applicability of a structural product manufactured from a cement-free geopolymer mixture composed entirely of waste and natural materials was analytically evaluated. In addition to industrial wastes such as waste tires, marble dust, bottom ash, and recycled concrete, the incorporation of abundant natural resources available in Türkiye was intended to contribute to the national Zero Waste Vision. The findings suggest that geopolymer mixtures can offer effective solutions for the construction industry. Analytical assessments revealed that geopolymer material could be utilized in various construction applications, including paving blocks, curbstones, barriers, foundation elements, and subfloor insulation.

However, the study did not include a comparative analysis of the production process or cost evaluation relative to existing systems. In this context, to facilitate the integration of waste tire-based geopolymer mixtures into the industry, comparative cost and life cycle assessments may be required. Although the mixture does not contain cement, the cost of preparing alkaline activators remains a significant parameter in large-scale production. Nevertheless, the classification of other components as waste materials and their ease of accessibility are expected to have a favorable impact on overall costs. Once the analyses are completed, the sectoral use of waste tire-based geopolymer products can be comprehensively evaluated in terms of cost-effectiveness and performance. Furthermore, it was concluded that combining the developed material with other construction materials could lead to advanced and innovative solutions. Analytical studies indicated that unit elements produced from this mixture could be coated with different materials and employed as infill walls within reinforced concrete frame systems. The damping effect of the material was also considered to offer beneficial contributions to frame behavior under lateral loads. In future studies, it is planned to investigate this effect experimentally with quasi-dynamic experiments to be carried out on scaled frame systems.

Through this study, it is aimed to contribute to both industrial and academic efforts in the areas of waste recycling, sustainability, reduction of carbon emissions, valorization of waste materials, and the design of advanced construction materials and innovative structural products.

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